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Numerical Simulation of the Development of Density Waves in a Long Pipeline and the Dynamic System Behaviour

Abstract

Slurry transport is used in dredging and mining to transport solid/liquid mixtures over a long distance and very frequently multiple pumps are utilised. To describe the processes involved, very often a steady state approach is used. A steady state process, however, requires a constant density and solids properties in the system and thus at the suction mouth. In practice it is known that the solids properties and the density change with respect to time. The density waves generated at the inlet of the system tend to transform their shape while moving along a pipeline. Under suitable conditions (a partially-stratified flow, low mean velocity of the mixture) high density waves tend to be amplified. This process is associated with the hydrodynamic interaction between the granular bed at the bottom of a pipeline and the suspension stream above the bed. The strongest amplification of high density waves occurs at mixture velocities around or below the deposition limit value. The development of density waves and the mechanisms leading to the deformation of density waves were discussed recently (Matousek, 2001).

A numerical model that uses a simplified description of mechanisms governing the unsteady flow of partially stratified slurry in order to simulate a development of a density wave along a long horizontal pipeline is presented. The model is two-dimensional; it handles the 2-D mass exchange within slurry flow. The vertical exchange of mass between the bed and the suspension layer above the bed is quantified using applied equations for the settling rate and the erosion rate. The adopted erosion-rate equation is preliminary and requires further investigation.

As a result of density fluctuations, the pump discharge pressure and vacuum will change with respect to time

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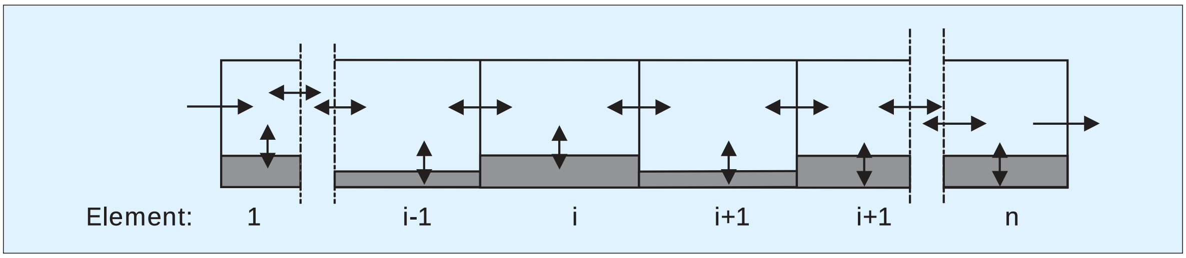

Figure 1. Elements of a pipeline filled with unsteady solids flow.

and the pipeline resistance will change with respect to time and place. A change of the discharge pressure will result in a change of the torque on the axis of the pump drive on one hand and in a change of the flow velocity on the other hand. The mixture in the pipeline has to accelerate or decelerate. Since centrifugal pumps respond to a change in density and solids properties at the moment the mixture passes the pump, while the pipeline resistance is determined by the contents of the pipeline as a whole, this forms a complex dynamic system. The inertial pressure of the mixture has to be added to the resistance of the mixture. In fact, the inertial pressure is always equal to the difference between the total pressure generated by the pumps and the total resistance of the mixture in the pipeline system. If this difference is positive (the pump pressure has increased as a result of an increase of the mixture density), the mixture will accelerate. If negative, the mixture will decelerate (Miedema, 1996).

As a result of the acceleration and deceleration, the mixture velocity (line velocity) will vary as a function of time. To realise a stable dredging process, it is necessary to have a line velocity that will not vary too much. The line velocity can be controlled by varying the revolutions of one of the dredge pumps, where the last pump is preferred.

Of course the result of flow control depends on the pump/pipeline layout. If this layout has not been designed properly flow control cannot correct a bad design. If this layout however has been well designed, flow control can control the line speed and can prevent the occurrence of cavitation.

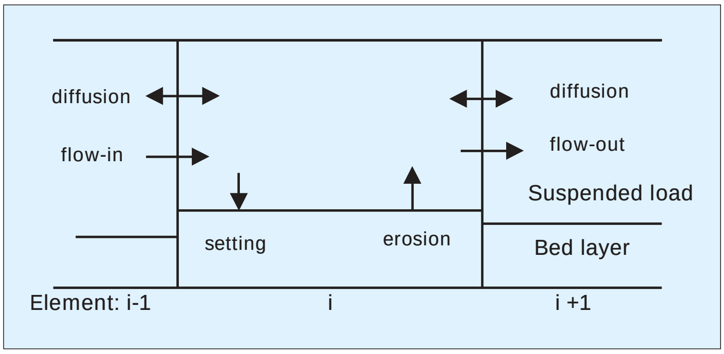

Figure 2. The transport phenomena simulated by the 2-D model.

Introduction

During dredging operations the density of mixture transported along the pipeline of a conveying system varies in time and space. The density waves generated at the inlet of the system tend to transform their shape while moving along the pipeline. This process is associated with the hydrodynamic interaction between the granular bed at the bottom of a pipeline and the suspension stream above the bed. The strongest amplification of high density waves occurs at mixture velocities around or below the deposition limit value.

The development of density waves and the mechanisms leading to the deformation of density waves were discussed recently (Matousek, 1997, 2001; Talmon, 1999).

Previously, the stratified flow in the long pipeline was analysed by using the principles of a two-layer model with a fixed position of the interface between the layers. A two-layer model is a one-dimensional model that simplifies the internal structure of a settling-mixture flow into a flow pattern composed of a particle-rich lower layer and a particle-lean upper layer. The analysis of the wave-amplification process in a long pipeline requires further refinement to implement the effects of the mass exchange caused by the settling flux and the erosion flux through the interface between the layers.

The modelling of the density-wave deformation requires that a one-dimensional two-layer model (longitudinal solids transport only) is replaced by a two-dimensional layered model that takes into account the vertical exchange of solids between the contact bed and the flow of suspension above the bed.

A model predicting the amplification of a density wave as a result of the exchange of solids mass in the direction perpendicular to the flow direction requires successful formula for both the settling flux and the erosion flux through the (virtual) interface between layers. The fluxes seem to be very sensitive to solids concentration at the interface, as must also be the formula determining the fluxes. As yet, the pick-up functions available for the prediction of the erosion flux are not reliable in the high concentrated flows typical for slurry pipelines.

Description of the 2-D Model for Unsteady Flow of Solids in a Pipeline

Model structure

If the flow of solids is unsteady the flow structure (the velocity and concentration profiles) varies not only in time but also in space, i.e. along a pipeline length. To be able to simulate the unsteady flow on basis of its internal structure, important parameters in both time domain and space domain must be identified. To handle the simulation in space domain properly, a pipeline must be divided into a number of elements. The flow in each element is split into two layers: the lower layer represents a granular bed (either stationary or sliding) and the upper layer represents the suspension flow. Since the solids flow is unsteady (the density of slurry varies along the pipelines and thus is different in different elements), the bed thickness is considered to be different in different elements. Figure 1 shows a slurry pipeline divided into elements for the model purposes.

Modeled transport phenomena

The conservation of mass must be satisfied in the model. The mass exchange takes place in two directions: horizontal and vertical. The horizontal transport of solids (the transport due to the pressure gradient in a pipeline) is given by the following equation

$$dm = Q \cdot t \cdot C_{v,up} \rho_s \qquad [1]$$

in which *dm* is mass differential in an element; *Q* is the flow rate of slurry; *t* is the time step; $C_{v,up}$ is the volumetric concentration of solids in the upper layer and ρ_s is the density of the solid. During the simulation, at each moment given by *t*, the $C_{v,up}$ is the only variable in different elements along the pipeline, the flow rate of slurry is considered constant.

The horizontal transport of solid particles is influenced by horizontal turbulent diffusion, other possible effects as those of interparticle collisions are neglected. In the vertical direction, the mass exchange can be defined into two processes: settling and erosion. The Figure 2 summarises the transport phenomena implemented in the 2-D model of unsteady flow of solids in a slurry pipeline.

Diffusion

The turbulent-diffusion process is quite complex. In the simplified way, it can be modelled as similar to the molecular diffusion using

$$f_{dif,x} = -k_x \cdot \frac{\partial \overline{c}}{\partial x} \qquad [2]$$

in which $f_{dif,x}$ is the diffusion flux owing to turbulence in the x-direction and kx is the factor of longitudinal dispersion. A suitable value for the factor k_x is subject to further investigation. The factor seems to be sensitive to the pipe diameter, particle size, slurry velocity and concentration. At this stage of investigation, the effect of turbulent diffusion is not taken into account in the 2-D model.

Settling

The dis-equilibrium between the solids settling rate and the erosion rate leads to the solids transport in the vertical direction (perpendicular to the main flow direction). This causes changes in the thickness of the bed and in the volumetric concentration of solid particles in the upper layer.

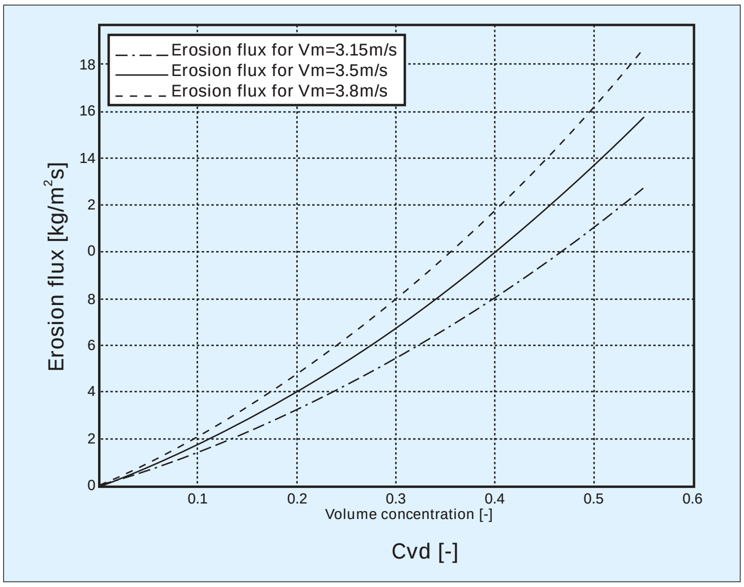

Figure 3. The erosion flux using the classical formula (Eqs. 4) for different solids concentrations and mean velocities of slurry in a pipeline.

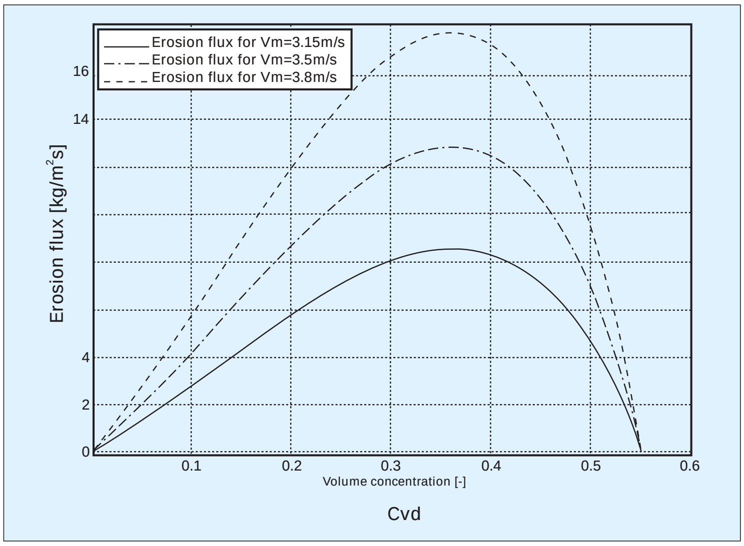

Figure 4. The erosion flux using the adapted formula (Eq. 7) for different solids concentrations and mean velocities of slurry in a pipeline.

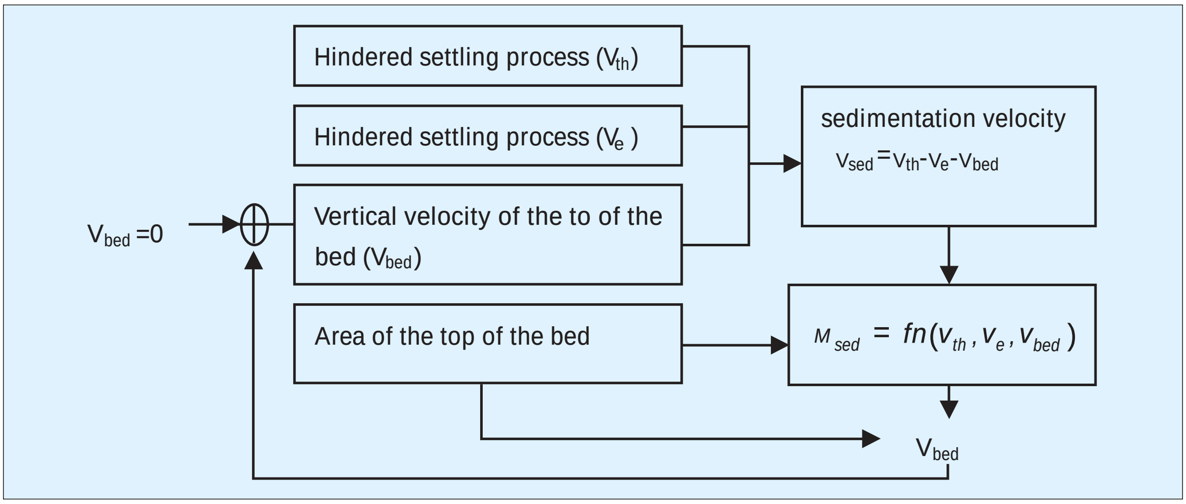

Figure 5. Computation of vertical mass exchange in the 2-D model.

Settling process presents the ability of the particles to settle from upper layer to the bed layer. Normally hindered settling velocity is applied to determine the settling process. It is derived as

$$v_{th} = v_t \cdot (1 - C_{v,up})^{m} \quad [3]$$

in which v_{th} is the hindered settling velocity of solid particles; v_t is the terminal settling velocity of a solid particle and m is the empirical Richardson-Zaki coefficient.

Erosion

The velocity of the suspension flow above the bed is higher than the bed velocity. If the velocity differential is high enough, the top of the bed is eroded. During the erosion process the particles from the top of the bed can be picked up by the suspension flow. The parameter called the erosion velocity evaluates the capability of the suspension flow to pick up particles from the granular bed. The erosion velocity has an opposite direction to the settling velocity. The equation for the erosion velocity is called the pick-up function.

Basically, the erosion velocity (the erosion rate) is dependent on the Shields number. The Shields number increases with the increasing relative velocity of the flow above the bed. The literature proposes a number of erosion-rate models. Unfortunately, the models are constructed for conditions rather different from those in slurry pipelines, i.e. namely for flow of water or very low-concentrated mixture above a stationary bed (see e.g. Van Rijn 1984, Cao 1997, Fernandez-Luque 1974). The equation for the erosion velocity

$$v_e = 1.1 \cdot (\theta - \theta_{cr}) \quad [4]$$

is used to plot the erosion flux in Figure 3. In Equation 4, θ is the Shields number and θ_{cr} is the critical Shields number (the threshold value for the initial erosion).

The erosion flux is calculated as

$$E = \rho_s \cdot v_e \cdot C_{vd} \quad [5]$$

Observations in a slurry pipeline indicate that the shear stress at the top of the bed and so the Shields number may vary significantly with the concentration of solids above the bed (e.g. Matousek, 1997). The classical erosion-velocity formulae do not include the effect of the solids concentration directly. For the purposes of slurry pipelines this parameter should be implemented to the erosion-velocity equation. Furthermore, in the classical erosion-velocity formulae the exponent of Shields number is usually considered higher than 1.

This means that the erosion flux simply keeps increasing with the increasing Shields number and so with the increasing solids concentration C_{vd}. This provides unrealistically high values of erosion flux in highly concentrated flows as shown on Figure 3.
However, it can be expected that at extremely high concentrations of solids the hindering effects reduce the erosion process (Talmon 1999, Van Rhee and Talmon, 2000) so that the erosion rate diminishes.

There are research results available on the effect of solids concentration on the erosion rate in a slurry pipeline. Therefore, as an initial approach, the hindering effect was considered here as similar to that for the solids settling so that the hindering effect can be represented in the erosion-rate formula by the term $(0.55 - C_v)^{\gamma}$. The erosion velocity is then determined using the following equation

$$v_e = \alpha \cdot (\theta - \theta_{cr})^{\beta} (0.55 - C_{v,up})^{\gamma} \quad [6]$$

in which β,γ are the empirical coefficients. The constant 0.55 represents the concentration of solids in a loose-packed bed. The calibration of this simplified equation using a limited number of data (see below) led to the following preliminary form of the erosion-velocity equation

$$v_e = 1.1 \cdot (\theta - \theta_{cr})^{1.9} \cdot (0.55 - C_{vd})^{0.9} \qquad [7]$$

This adapted erosion-rate equation provides a rather different shape of the curve than the classical model (compare Figures 3 and 4). The adapted model seems to provide more realistic trends, but it must be stressed that the form of the model and the values of the coefficients have not been verified by experiments. A final form of the erosion-rate equation for slurry pipelines is a subject for further investigation.

Mass exchange between bed and suspension flow

If there is dis-equilibrium between the settling flux and the erosion flux, the mass exchange takes place between the granular bed and the suspension flow and the thickness of the bed varies. The relative velocity that represents the mass exchange is called the sedimentation velocity, v_{sed}, and can be defined as

$$v_{sed} = v_{th} - v_e - v_{bed} \qquad [8]$$

In Eq. 8, v_{bed} is the velocity of the top of the bed, i.e. the vertical velocity with which the top of the bed changes its position.

The sedimentation velocity represents the mass exchange between the contact bed and the suspension flow properly for channels in which the area through which the mass fluxes release does not change with the vertical position of the top of the bed, i.e. for rectangular channels. In circular pipelines, however, the area of the top of the bed varies significantly the vertical position of the top of the bed (with the bed thickness), and then an iteration is required to determine the sedimentation-velocity value. The iteration process is described in Figure 5.

SIMULATIONS

The 2-D model is calibrated and tested using the data obtained from the measurements in a long 650-mm pipeline transporting the medium sand of d_{50} = 250 microns (for details over the measurements and data see Matousek 1997 and Matousek 2001).

Relation between settling and erosion fluxes

The measurements have shown that in flow near the deposition-limit velocity density peaks smaller than approximately 1250 kg/m^3 tended to flatten along the long horizontal pipeline while peaks larger than approximately 1400 kg/m^3 tended to amplify. Considering the vertical exchange of solids between the bed and the suspension as the mechanism responsible for the density-wave transformation, the observed phenomena can be interpreted as follows. In suspensions of density

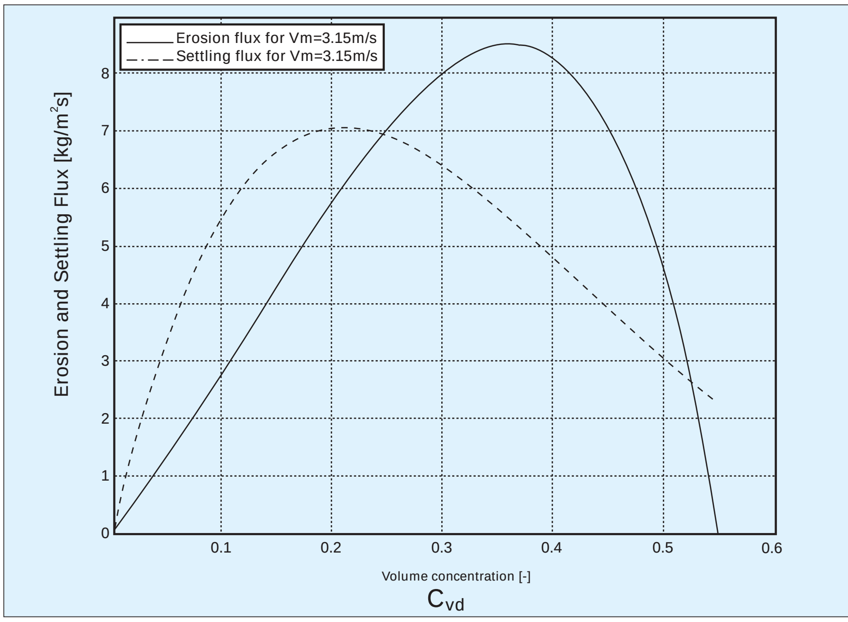

Figure 6. Comparison of settling and erosion fluxes according to the 2-D model in a 650-mm pipeline occupied by slurry of medium sand (d_{50}=0.25 mm) (V_m=3.15 m/s).

lower than approx. 1250 kg/m^3 the settling flux is bigger than the erosion flux, thus a portion of solid particles is transferred from the suspension to the bed, the thickness of the bed increases. In denser suspension (approx. denser than 1400 kg/m^3) the erosion flux from the top of the bed predominates and the particles are picked up from the bed, the density of suspension increases and the bed thickness decreases.

The adapted erosion-flux formula (Eq. 4) can be calibrated using the experimental data so that the calculated disequilibrium (see Figure 6) for the velocity near the deposition-limit value (3.15 m/s) shows the same trends as the measurements. The plot shows that for the above chosen conditions the model predicts the equilibrium between the settling flux and the erosion flux in slurry of the volumetric concentration of about 0.25 (slurry density of about 1415 kg/m^3). In the parts of the pipeline that are occupied by the slurry of density lower than this value the model predicts the predomination of the settling flux and thus gradual decrease of solids concentration in the suspension flow. In the parts occupied by the slurry of density higher than 1415 kg/m^3 (and lower than approximately 1930 kg/m^3) the model predicts the dominant effect of the erosion and thus a gradual increase of solids concentration in the suspension flow. The amplification of the high-density peaks does not occur at velocities significantly higher than the deposition-limit velocity. This is because the majority of particles are supported by turbulence (travels within suspension flow) and the bed is very thin. Under this condition the interaction is missing between two layers that is necessary for the development of the density waves.

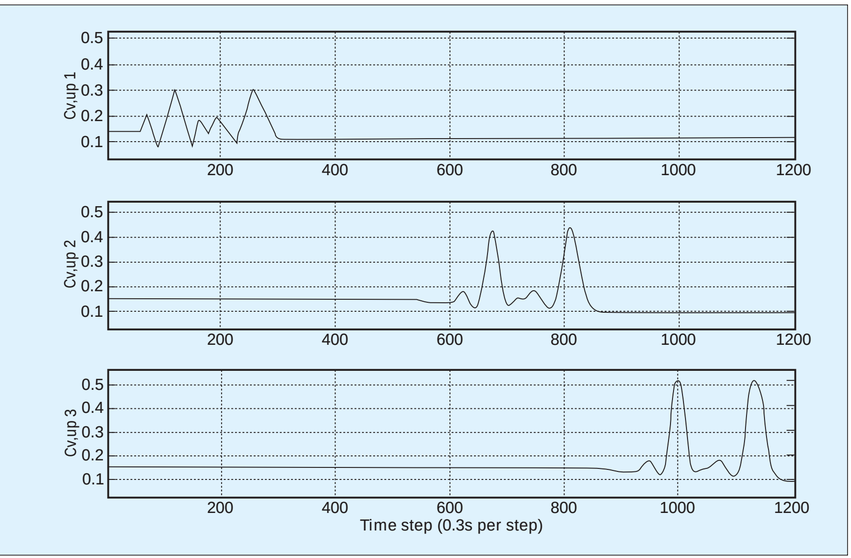

Figure 7. Deformation of density waves along the long pipeline (slurry velocity round the deposition limit velocity) observed at the inlet to the pipeline, 500 metres behind the inlet and 800 metres behind the inlet.

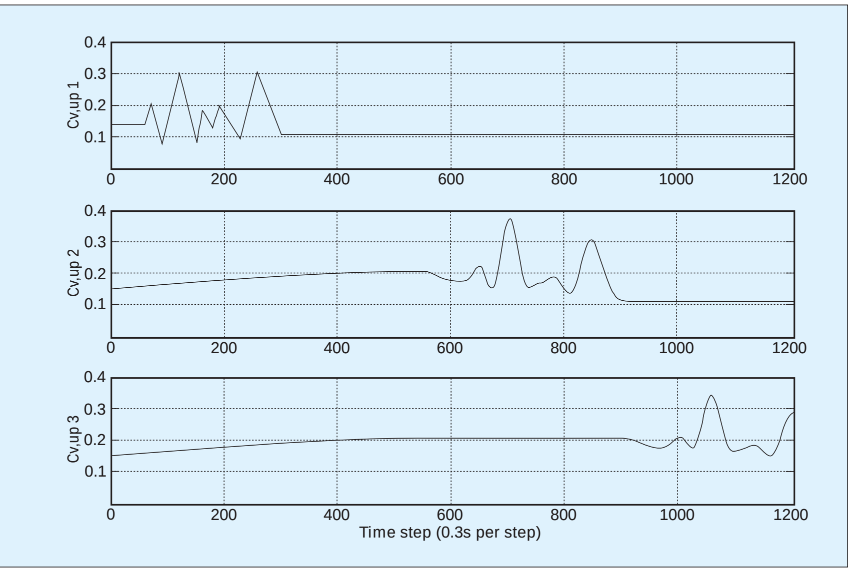

Figure 8. Deformation of density waves along the long pipeline (slurry velocity far above the deposition limit velocity) observed at the inlet to the pipeline, 500 metres behind the inlet and 800 metres behind the inlet.

The model with the implemented flux equations for vertical mass exchange can simulate a deformation of the density waves along a long horizontal pipeline. The plots in Figures 7 and 8 show the simulation results for the conditions described above (a pipeline of the diameter 650 mm and sand 250 microns). The pipeline is 1200 m long and the simulated time period is 360 seconds. One time step in the simulation represents 0.3 second, i.e. 1200 steps are made during the entire simulation. The plots in the Figures 7 and 8 indicate the volumetric concentration of solids in the suspension flow simulated in the element 1 (the position at the inlet to the pipeline), element 500 (the position 500 metres behind the inlet) and the element 800 (800 metres behind the inlet). The figures show how the set of density waves changes its shape while passing through the pipeline.
In Figure 7, the slurry pipeline operates at the mean slurry velocity round the deposition-limit velocity (3.15 m/s). There is a granular bed of a considerable thickness at the bottom of the pipeline. The simulation indicates that owing to the vertical exchange of mass between the bed and the suspension flow above the bed two large density peaks gradually increase and three small peaks gradually decrease while passing through the long pipeline from element No.1 to No. 800. These trends are in accordance with those observed in the field pipeline during the tests (Matousek 2001).

In Figure 8, the slurry pipeline operates at the mean slurry velocity far above the deposition-limit velocity (3.8 m/s). At this velocity the sliding bed at the bottom of the pipeline is very thin and tends to dissolve. This is primarily owing to higher ability of carrier turbulence to keep particles suspended and also owing to higher erosion than at velocity 3.15 m/s. Under these conditions the deformation of the density waves is different from that in the pipelines occupied by a thick bed.

The waves change their shape much less than in the layered flow as can be seen in Figure 8. The front peaks of the set of the peaks tend to increase after entering the pipeline but their increase stops when the bed disappears in the pipeline and there is no material to feed the peaks. The rest of the peaks do not grow for the same reason. The increase of concentration of solids to the limit value 0.20 in the suspension flow in front of the set of the peaks in elements No. 500 and No. 800 indicates that the bed dissolved there already before the set of the peaks arrived. The concentration value 0.20 was reached when all particles traveled in suspension, thus there was no bed.

The Pump/Pipeline System Description

In a steady state situation, the revolutions of the pumps are fixed, the line speed is constant and the solids properties and concentration are constant in the pipeline. The working point of the system is the intersection point of the pump head curve and the pipeline resistance curve. The pump curve is a summation of the head curves of all pumps. The resistance curve is a summation of the resistances of the pipe segments and the geodetic head. Figure 9B shows this steady state situation for the system used in the case study (Figure 9A) at 6 densities ranging from clear water up to a density of 1.6 ton/m^3. In reality, the solids properties and concentration are not constant in time at the suction mouth. As a result of this, the solids properties and concentration are not constant as a function of the position in the pipeline.

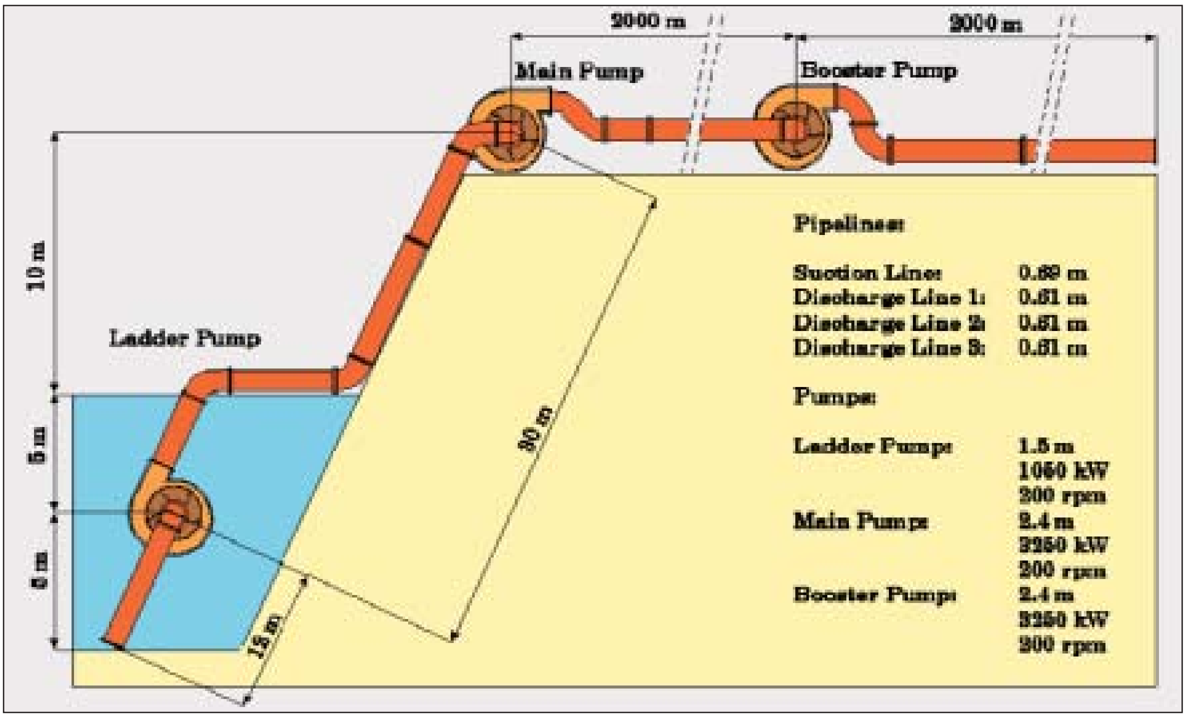

Figure 9A. The pump/pipeline system used.

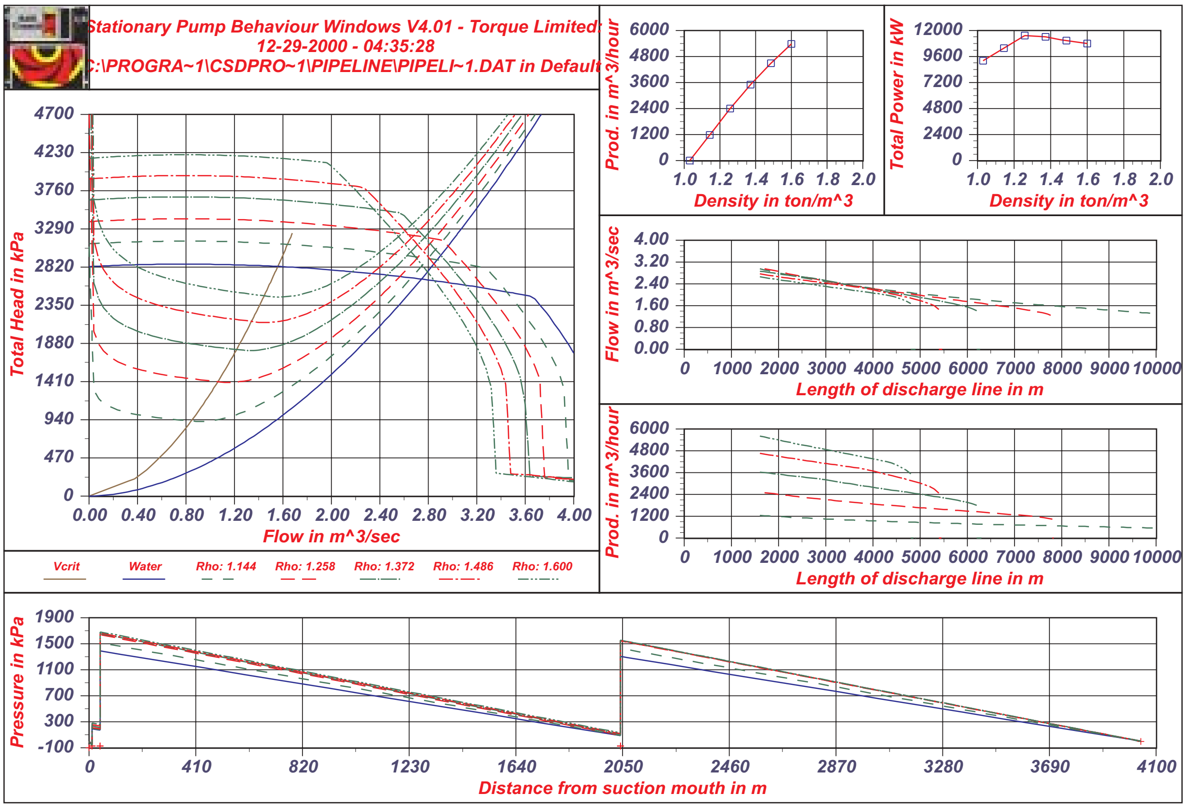

Figure 9B. Characteristics of the pump/pipeline system.

To be able to know these properties as a function of the position in the pipeline, the pipeline must be divided into small segments according to the above discussions. These segments move through the pipeline with the line speed. Each time step a new segment is added at the suction mouth, while part of the last segment leaves the pipeline. Because the line speed is not constant, the length of the segment added is not constant, but equals the line speed times the time step. For each segment the resistance is determined, so the resistance as a function of the position in the pipeline is known. This way also the vacuum and

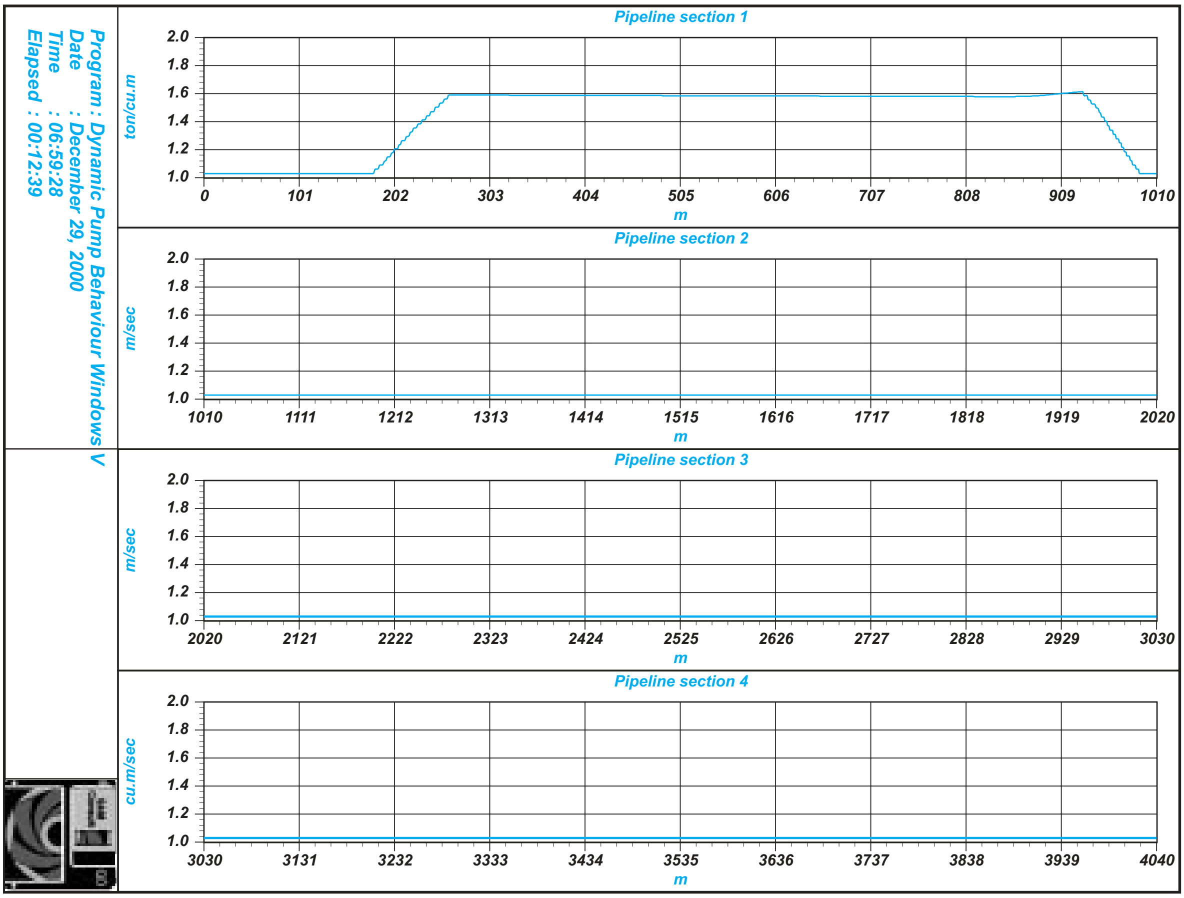

Figure 10. The density distribution in the pipeline after 12 minutes.

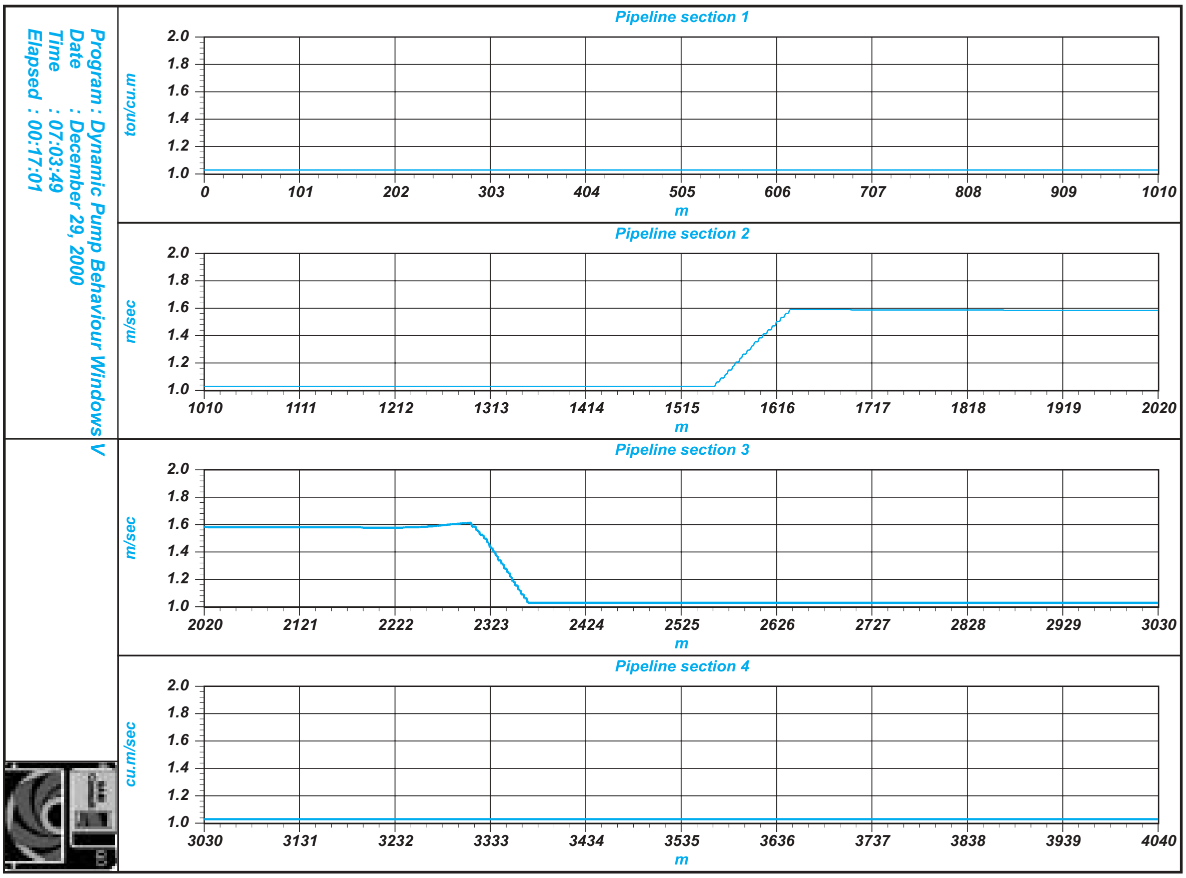

Figure 11. The density distribution in the pipeline after 17 minutes.

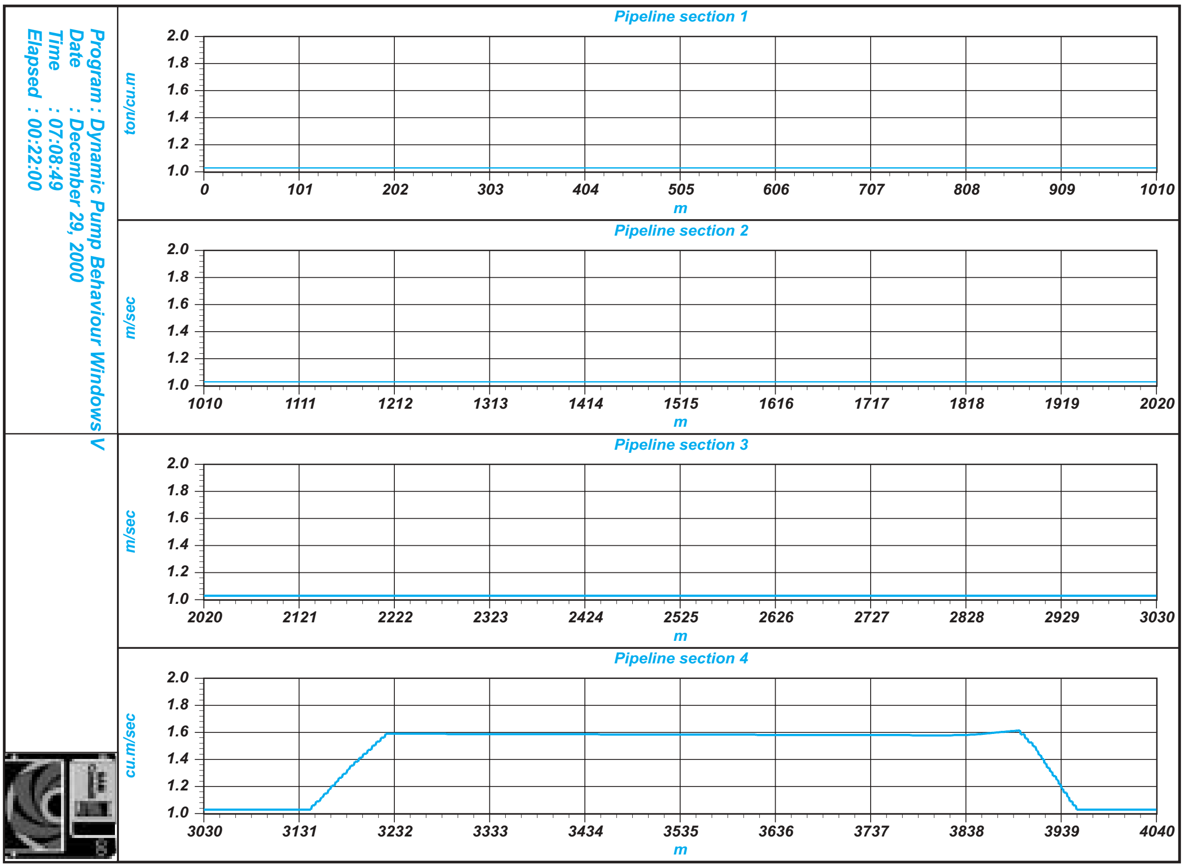

Figure 12. The density distribution in the pipeline after 22 minutes.

the discharge pressure can be determined for each pump. If vacuum results in cavitation of one of the pumps, the pump head is decreased by decreasing the pump density, depending on the time the pump is cavitating.

Case Study

The aim of this case study is twofold; first it shows events caused by the dynamic behaviour of the system that cannot be predicted by steady state calculations; second it shows the application of the above theory of density waves. A problem in defining a system and a scenario for the simulation is, that the system can consist of an infinite number of pump/pipeline combinations, while there also exists an infinite number of solids property/concentration distributions as a function of time. For this case study, a system is defined consisting of a suction line followed by three pump/pipeline units (see Figure 9A). The first pump is a ladder pump, with a speed of 200 rpm, an impeller diameter of 1.5 m and 1050 kW on the axis (see Figure 9A). The second and the third pump run also at a speed of 200 rpm, have an impeller diameter of 2.4 m and 3250 kW on the axis. The time constants of all three pumps are set to 4 seconds. The time constant of the density meter is set to 10 seconds. The suction line starts at 10 m below water level, has a length of 12 m and a diameter of 0.69 m. The ladder pump is placed 5 m below water level. The main pump and the booster pump are placed 10 m above water level. The pipeline length between ladder and main pump is 30 m, between main pump and booster pump 2000 m, as is the length of the discharge line. The pipe diameters after the ladder pump are 0.61 m. The total simulation lasts about 30 minutes and starts with the pipeline filled with water.

After the pumps are activated, the mixture density at the suction mouth increases to a density of 1.6 ton/m^3, stays at that value for a period of 2 minutes and then decreases back to the water density.

Sand is used with a d_{15} of 0.25 mm, a d_{50} of 0.50 mm and a d_{85} of 0.75 mm. The density block wave moves through the system, subsequently passing the three pumps.

For the simulation the following scenario is used:

00 minutes	start of simulation, the timer is started and all parameters will be recorded
01 minutes	start of ladder pump, the ladder pump drive behaves according to a first order system
04 minutes	start of main pump, the main pump drive behaves according to a first order system
07 minutes	start of booster pump, the booster pump drive behaves according to a first order system
08 minutes	start of the flow control system (optional)

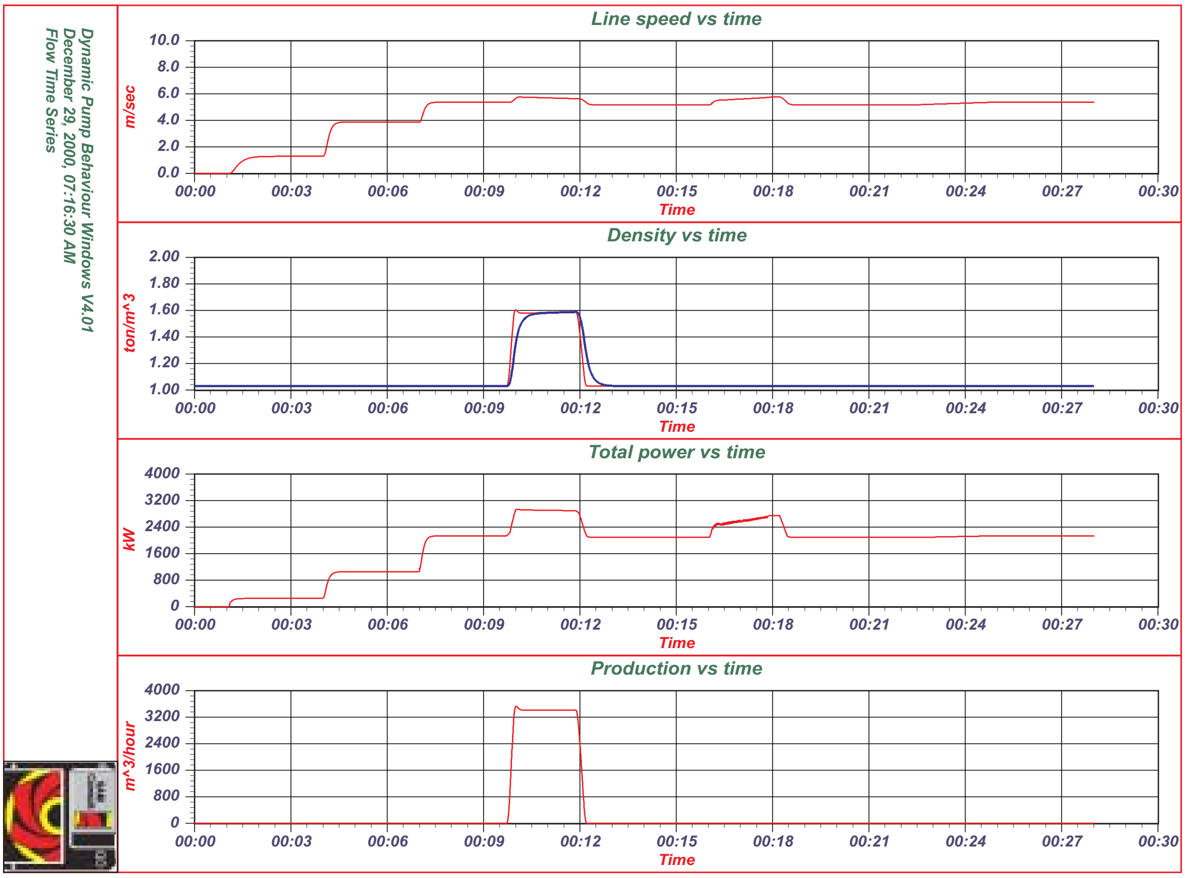

Figure 13. Line speed, density, total power and situ production as a function of time.

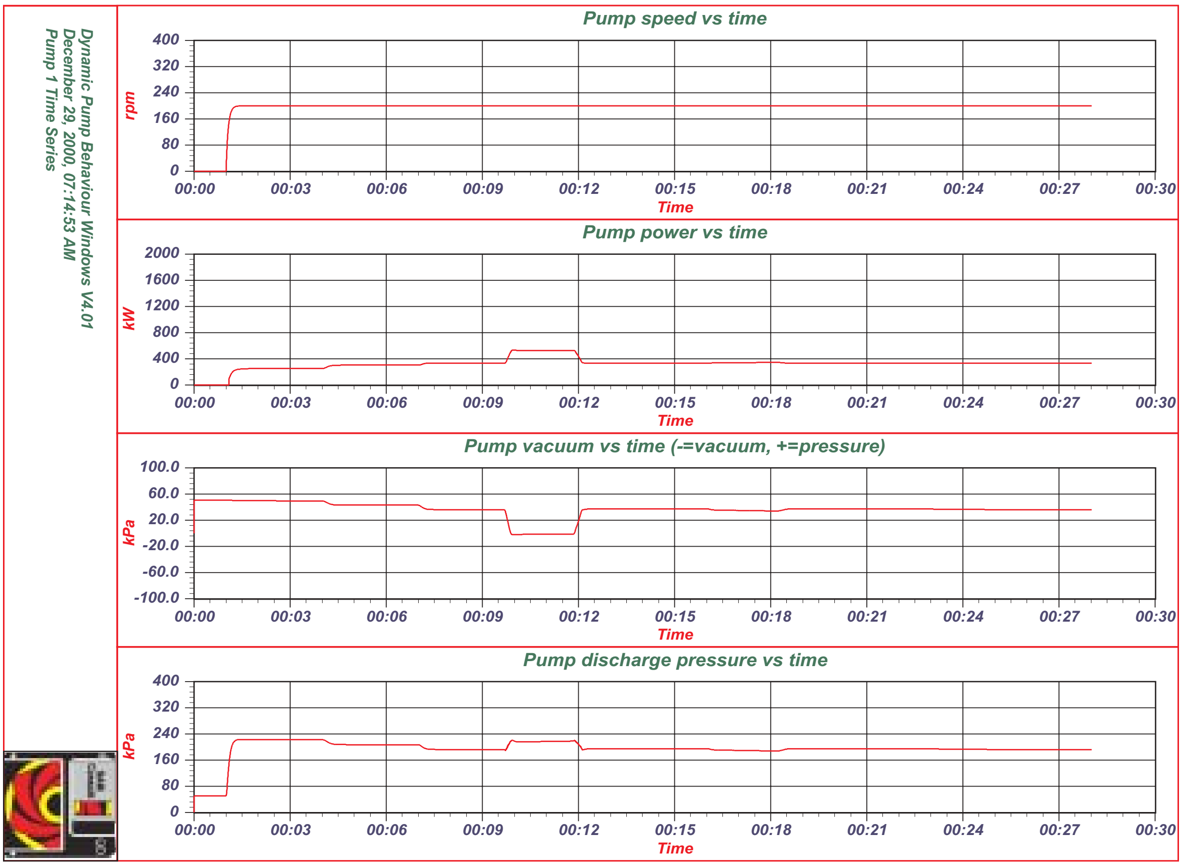

Figure 14. Speed, power, vacuum and discharge pressure of the ladder pump vs. time.

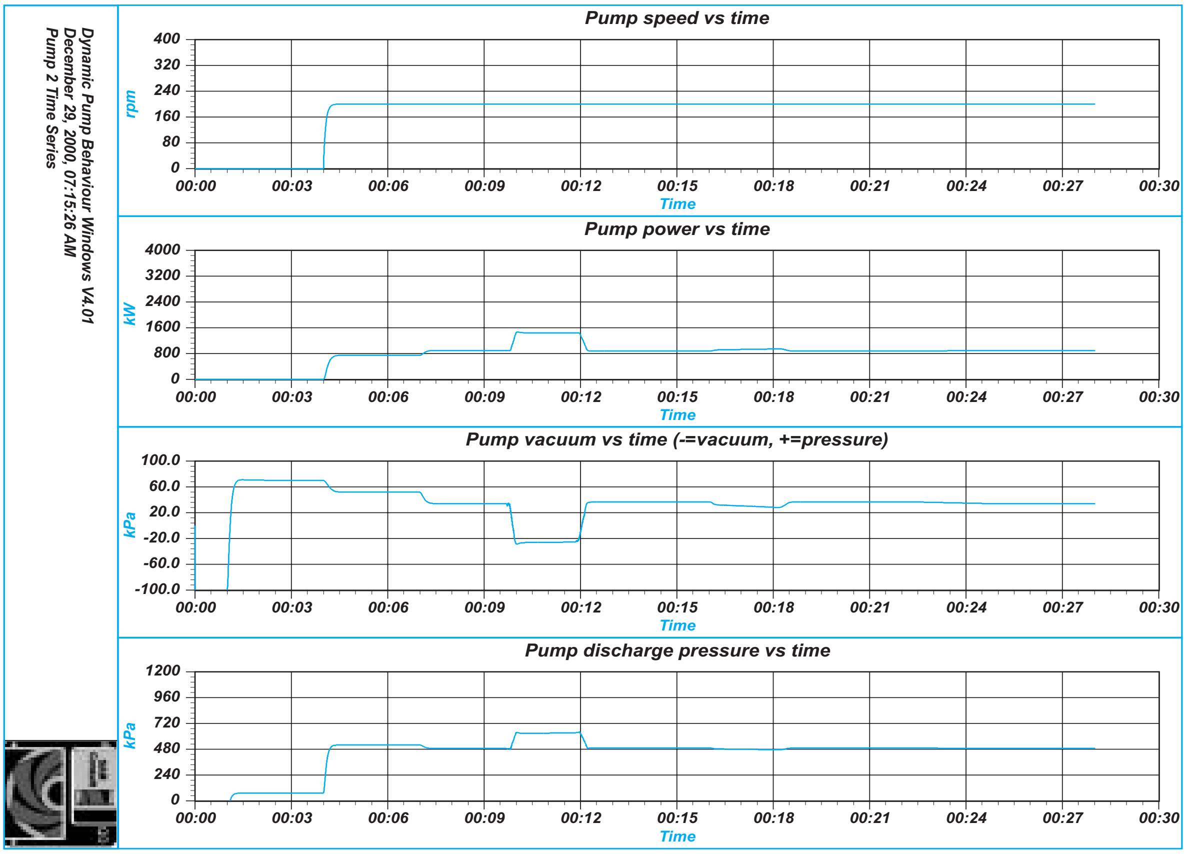

Figure 15. Speed, power, vacuum and discharge pressure of the main pump vs. time.

10 minutes increase mixture density to about 1.6 ton/m^3
12 minutes decrease mixture density to water density
12 minutes take sample of density distribution in pipeline
17 minutes take sample of density distribution in pipeline
22 minutes take sample of density distribution in pipeline
28 minutes stop simulation and create graphs

Figures 10, 11 and 12 show the density wave at 12, 17 and 22 minutes of simulation time. At 12 minutes the density wave occupies the suction line, the ladder pump and the main pump and part of the pipeline behind the main pump. At 17 minutes the density wave occupies the last part of the pipeline before the booster pump, the booster pump and the first part of the discharge line after the booster pump.
At 22 minutes the density wave occupies the middle part of the discharge line.

Figure 13 shows the line speed, the density, the total power consumed and the production as a function of time. The line speed, the density and the production are determined at the inlet of the ladder pump.

The density is determined using the mathematical behaviour of a density transducer with a time constant of 10 seconds. Figures 14, 15 and 16 show the pump speed, power, vacuum and discharge pressure of the three pumps as a function of time.

As can be seen in Figure 13, the line speed increases slower then the pump speed, owing to the inertial effect. When the density wave passes the ladder and main pump (from 10 to 13 minutes), the discharge pressure of these pumps increases, resulting in a higher line speed. When the density wave passes the booster pump (from 16 to 19 minutes) the same occurs for the booster pump. After about 10 minutes of simulation time, all three pumps are activated and a steady state situation occurs in the system.
Then the mixture density at the suction mouth increases from water density to about 1.6 ton/m^3. First the resistance in the suction line increases, resulting in a sudden decrease of the ladder pump vacuum and discharge pressure. When the density wave reaches the ladder pump, the discharge pressure increases, owing to the higher density. When after 2 minutes, the density decreases to the water density, first the resistance in the suction line decreases, resulting in an increase of the ladder pump vacuum and discharge pressure, followed by a decrease of the discharge pressure when the clear water reaches the ladder pump (see Figure 13). The distance between the ladder pump and the main pump is 30 m. With an average line speed of 5 m/s, the density wave passes the main pump 6 seconds after passing the ladder pump.

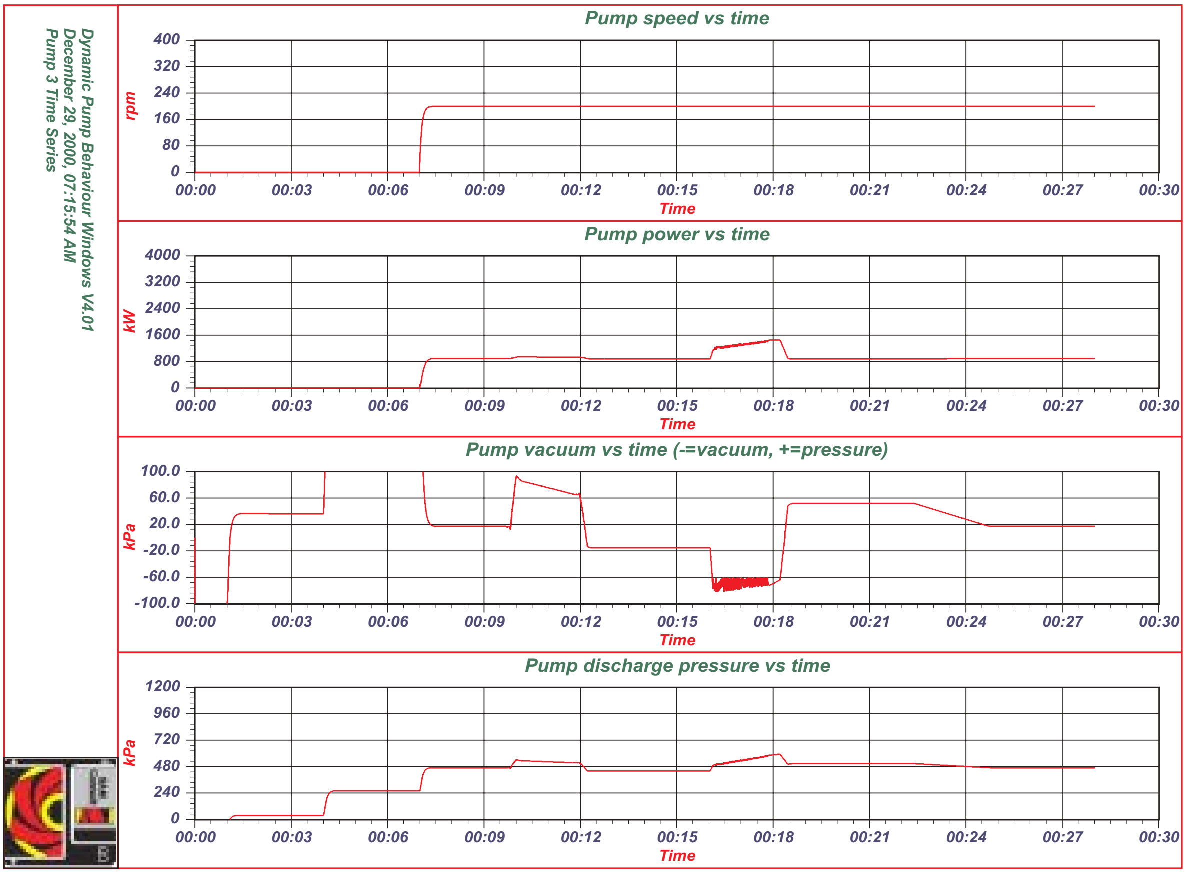

Figure 16. Speed, power, vacuum and discharge pressure of the booster pump vs. time.

The same phenomena as described for the ladder pump, occur 6 seconds later for the main pump (see Figure 15). As a result of the increased discharge pressure of ladder and main pump during the density wave, the line speed will also increase (see Figure 13), but because of the inertial effects, this increase and 2 minutes later decrease is not as steep. One could say that there is a time delay between the immediate response of the discharge pressure of the pumps on changes in the density in the pumps and the response of the line speed on changes in the discharge pressure.

At 12 minutes and about 45 seconds, the density wave has left the main pump, but has not yet reached the booster pump. The head of each pump is determined by the density of water, but the line speed is still determined by the head resulting from the mixture and thus to high. The resistance in the pipe between main and booster pump is high because of the mixture, resulting in a decrease of the booster pump vacuum and discharge pressure. As the line speed decreases, the booster pump vacuum and discharge pressure will stay in a semi-steady state situation. When the density wave reaches the booster pump, the total head of the booster pump increases, resulting in an increase of the line speed. This occurs after about 16.5 minutes of simulation time. Since the total head of ladder and main pump does not change, the booster pump vacuum will have to decrease to pull harder on the mixture in the pipeline before the booster pump. This results in the occurrence of cavitation of the booster pump, limiting the total head of the booster pump and thus the line speed. The cavitation causes a very instable behaviour of the booster pump as is shown in Figure 16.

Since the density wave moves from the suction line to the discharge line, the booster pump vacuum and discharge pressure both increase when the density wave moves through the booster pump. After 18.5 minutes the density wave leaves the booster pump. The total head of the booster pump decreases sharply, while the line speed decreases slowly.

The fluid in the pipeline before the booster pump pushes and the fluid after the booster pump pulls, resulting in a quick increase of the booster pump vacuum and a decrease in the booster pump discharge pressure.

As the line speed decreases, the discharge pressure will increase again. After 23 minutes of simulation time, the density wave starts leaving the pipeline. Two minutes later the density wave has completely left the system. Because of the decreasing resistance during this timespan, the line speed will increase slightly, resulting in a small decrease of the vacuum and discharge pressure of each pump, while the total head remains constant.

The total power will also increase slightly because of this.

Conclusions

The simplified two-dimensional model has been proposed for simulation of dynamic effects of unsteady solids flow in a horizontal slurry pipeline. This model is a first attempt to simulate the deformation of density waves observed in long pipelines connected with a dredger.

The results of the model simulation show the same trends in the development of the density waves as those observed in practice. Both the physical process of the unsteady solids flow and its simulation require further investigation. Special attention must be focused to erosion in high concentrated slurries and effect of turbulent diffusion on the solids distribution in suspension flow.

The behaviour of a multi pump/pipeline system is difficult to understand. As mentioned before, an infinite number of system configurations and soil conditions exist. Systems are usually configured, based on steady state calculations, while the dynamic behaviour is ignored. Combining the steady state approach for pipeline resistance with the dynamic behaviour of pumps, pump drives and the second law of Newton, the dynamic behaviour can be simulated.

However, a number of assumptions had to be made. These assumptions are:
– there is no longitudinal diffusion in the pipeline,
– the pump drive behaves like a constant torque system,
– the pipeline resistance is determined using the Durand theory,
– the centrifugal pump obeys the affinity laws.

The simulations however show the occurrence of phenomena that are known in practice. The use of automation/flow control works well for the case considered, but many cases have to be considered to be sure the flow control is stable. In the case considered, the density measured has not been used for the flow control to surpress cavitation. Since the hydraulic transportation process is governed by different parameters, it is impossible to fully control the process by measuring just 1 parameter and controlling just 1 parameter. Whether these assumptions are valid will be subject of further research.

One should consider that mathematical modelling is an attempt to describe reality without having any presumption of being reality.

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